NASA'S SOLAR SYSTEM EXPLORATION PROGRAM

R. S. Saunders
Senior Member
Chief Scientist, Solar System Exploration Office
Jet Propulsion Laboratory / California Institute of Technology
Pasadena, California

ABSTRACT

As NASA's Solar System Exploration program enters its fifth decade, it continues to provide new discoveries, new excitement, and new insight into the origins, evolution, and destiny of our solar system, our planet, and life itself. With seven missions presently active, and another dozen scheduled for launch in the next five years, this unprecedented level of exploration and discovery promises to continue and even increase.

The overarching scientific goals for the Exploration of the Solar System are expressed as three Quests. The Quests form an engaging and compelling framework for the development of detailed scientific objectives, measurement priorities, and flight missions.
The missions of Solar System Exploration are conducted within several programs, each of which has an annual budget that covers mission development, launch, and operations. The three existing programs are the Outer Planets program, the Mars Surveyor program, and the Discovery program.

Exploration of the outer planets, from the early Pioneer and Voyager flybys to today's Galileo mission, has revolutionized our view of the solar system. In part, we have learned that the outer planets and their moons are rich in organic material, that subsurface liquid water may exist in some places, and that prebiotic chemical processes are taking place in some of these environments. The Cassini/Huygens mission, en route to Saturn, will extend this exploration by conducting an intensive study of Titan's atmosphere and surface.

The present Outer Planets Program focuses on environments in the outer solar system that can provide insight into prebiotic chemistry and the building blocks of life. The first two missions in this program, Europa Orbiter and Pluto/Kuiper Express are currently under development for launch in 2003 and 2004 respectively. Following those, the highest priority missions are the Europa Lander, Titan Explorer, and Neptune Orbiter . These will build on the results from the past, present, and upcoming missions and will conduct in-depth analyses of these organic-rich environments. Mission sequence decisions will be based on continuing scientific discoveries and the progress of technology developments.

Mars Surveyor is a program of systematic exploration and discovery that represents the nation's long-term commitment to exploring the planet Mars. The overarching scientific goals are to develop an understanding of the biological history and potential of Mars and to search for evidence of past or present life. The history of water and the Martian climate are key elements in this search and are thus critical near-term objectives. Over time, the program will establish Mars robotic outposts and a Mars-Earth communications infrastructure that will link the two planets as the first nodes in a "solar system internet". In the longer term, the program will help us to understand the potential for utilization of Martian resources and will lay the groundwork for future human exploration.

Discovery is a highly successful program of community-defined, competitively selected missions. Four missions have been launched so far – NEAR, Mars Pathfinder, Lunar Prospector, and Stardust - and four more are currently under development. A wide variety of solar system targets will be addressed within the Discovery program. Innovations within the program include "Missions of Opportunity" and Discovery Micromissions.

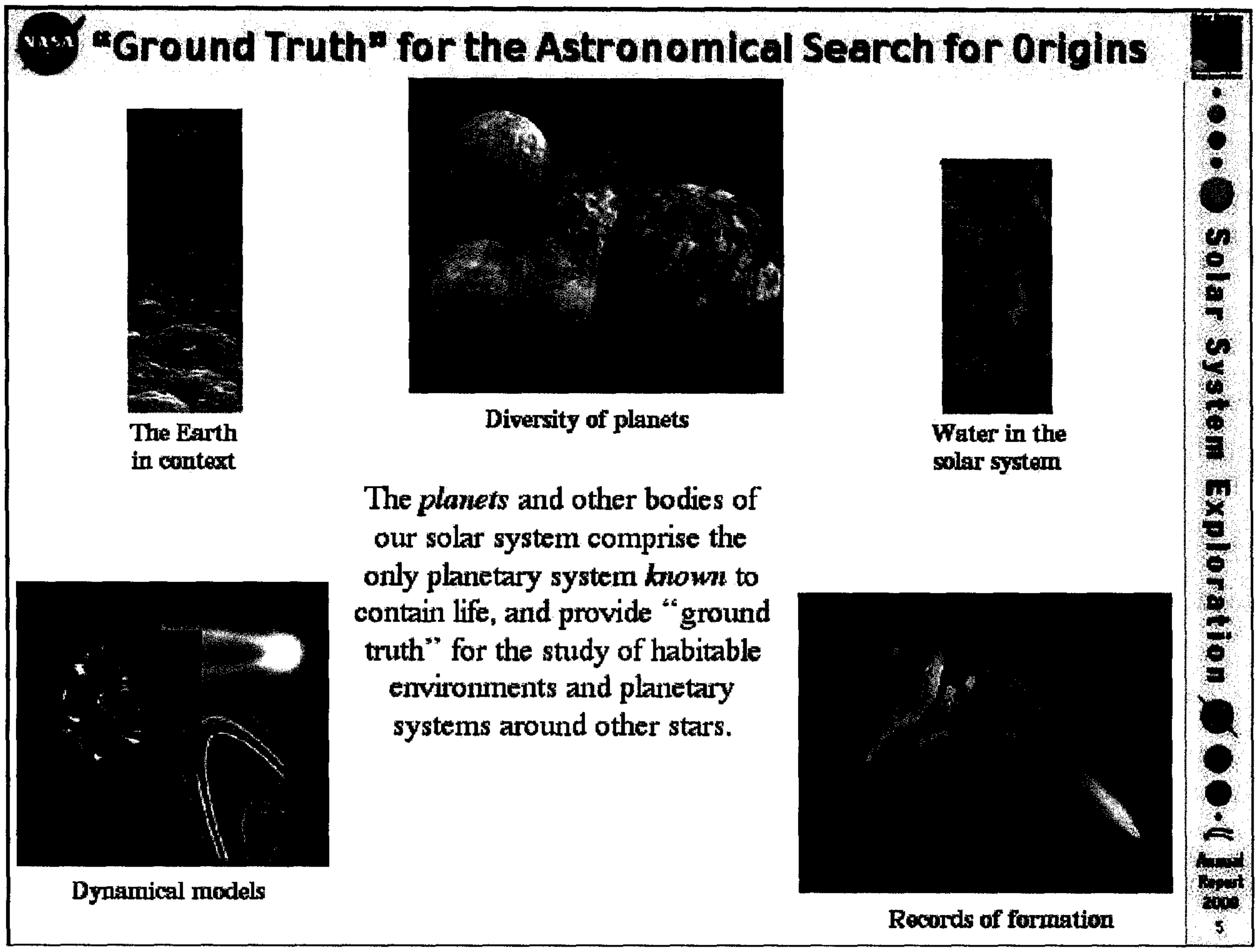
Missions to return samples of a comet nucleus and of Venus' surface will be key elements of the future program, and will expand our knowledge of the formation and evolution of planetary environments.

INTRODUCTION

Exploration of the Solar System is one of the four themes that comprise the science activities of NASA's Office of Space Science. The other three are: Structure and Evolution of the Universe, Sun-Earth Connection, and Search for Astronomical Origins and Other Planetary Systems. The Solar System Exploration Program seeks answers to fundamental questions about our Solar System and life. Initially, we seek to understand how planets form. What processes in the solar nebula are responsible for the compositions we see today? What factors led to the observed differences among the planets and satellites? We have observed some 80 planets and satellites in our Solar system. They all differ in significant ways, yet there are basic principles, common to all, that we can discover, that determine their initial state and govern their evolution. There are many puzzles that resist explanation. Some examples: Mercury is more dense than current theory can explain; why? Did Mercury form at a different location in the nebula than the position it now occupies? Where did the stuff for life come from? We know little about the source regions out in the Kuiper belt and beyond for comets. An early influx of cometary material may have brought in the volatiles and carbon that made life possible on Earth. Did life arise elsewhere in the Solar System, or is the Earth unique? Finally, how can we apply the knowledge we gain from exploration to understanding the ultimate fate of Earth, its future habitability, and the possibility of other places in the Solar System as a habitat for future human exporers. explorers

Thus the exploration of the Solar System addresses some of the most profound questions ever asked by mankind. We seek to understand the origin and evolution of planets, environments suitable for life in any form, and ultimately, of life itself. This is a fundamental part of the broader goal of Space Science, to search for Origins in the broadest sense, of planetary systems, Earth-like places, and life. In order to do this, we study the only planetary system known to harbor life, our own. This will help us search for other habitable environments in the universe and address the question: Are we alone?

The missions of Solar System Exploration are conducted within programs, each of which has a budget that covers development, launch, operations, and science data analysis. The three existing programs are the Outer Planets program, the Mars Surveyor program, and the Discovery program. The first two of these focus on particular scientific objectives, and missions are selected by NASA through the strategic planning process. The Discovery program is a scientifically broad program whose missions are competitively selected; they may complement the missions in the other two programs or they may independently address goals expressed in this Roadmap.



SOME SCIENCE HIGHLIGHTS OF THE PAST YEAR

The Galileo Jupiter mission has continued to provide exciting new discoveries. On the moon Io, a massive volcanic eruption from a rift was observed in progress. Imaging and magnetic data from of Europa have provided additional evidence for a salty subsurface ocean. Studies of Jupiter's atmosphere have revealed that thunderstorms provide a major energy source within the atmosphere and contribute energy to the general circulation of the atmosphere.

Hot lava (>1200 K) saturated the camera CCD image along the volcanic eruption (white areas). The geometry of the eruption was reconstructed from camera 'bleeding' calibrations.

DISCOVERY PROGRAM

Discovery is a program that solicits proposals from the science community. Each mission is capped at $300 million and must include partnerships between universities, industry and NASA centers. The program encourages new ideas for exploring the Solar System. Last year, Lunar Prospector completed its mission with a controlled lunar impact experiment after it met or exceeded all scientific objectives. The Near-Earth Asteroid Rendezvous mission went into orbit at Eros on Valentine's Day, 2000, and is returning excellent data. Stardust began interplanetary dust collection and is operating perfectly. Genesis, to study solar wind, and CONTOUR, which will study the diversity of comets, continue on track for launch in 2001 and 2002. Deep Impact, which will impact a comet with a 500 kg projectile to study its internal structure, and MESSENGER, which will study the local environment of Mercury, were selected for development and launch in 2004 and 2005.

EDUCATION AND PUBLIC OUTREACH ACTIVITIES

The Solar System Exploration Program is committed to sharing the excitement and the knowledge gained with all segments of the American public. Our goal is to enhance American education with real-life examples from our exploration of the unknown. Space exploration can motivate, stimulate and inspire our youth to take an active part in the future so they can take their part and contribute to a scientific and technical workforce that will keep the United States in the leadership role for advanced technologies and scientific research. The target audiences are the formal education community, informal education organizations and the general public. Education is an enormous segment of our economy, and we maximize our impact by creating partnerships to leverage resources and increase our reach. We know that space exploration is inherently fascinating, so we will engage our audiences and make Solar System exploration a part of the human experience.

The recent Near Earth Asteroid Rendezvous mission provides an example of public engagement activities. The NEAR - Shoemaker Orbit Insertion Event was broadcast via NASA TV and Quest February 14, 2000. During the event called Mission 2000: Operation NEAR - Shoemaker at APL we held student press conferences and provided an opportunity for young people to experience mission operations with Exploration Station mini-missions. Lesson plans were made available by cable in the classroom and through the Maryland State Department of Education. Other activities included NEAR Central with 3 days at Maryland Science Center and Parent and Child NEAR Week at the U.S. Space and Rocket Center. The NEARLink Congressional District Initiative, in collaboration with Space Explorers, Inc. provided one NEARLink education program in each U.S. Congressional District. This is only one specific mission example. All the flight programs have extensive outreach activities.

SCIENCE RESEARCH AND ANALYSIS PROGRAMS

Within Solar System Exploration there are several science discipline programs that fund U.S. scientists to perform research. This research supports the exploration activities in many ways. New concepts, hypotheses to test, come out of the research and this leads to new missions.

Planetary Geology and Geophysics determines and constrains the processes of planet formation and evolution. An important aspect of the research is to identify and research past / present habitats for possible life on Mars and beyond.

Cosmochemistry studies the chemical building blocks of small bodies (comets and asteroids, small moons), planets, and life.

Planetary Astronomy and Near-Earth Objects provides an inventory and nature of the physical building blocks of planetary systems. The researchers observe and model large-scale planetary. An important element is to inventory and characterize Near Earth Objects larger than one km; a goal is to complete the inventory within ten years to identify possible life threatening hazards to Earth.

Planetary Atmospheres tasks study atmospheric chemistry and dynamics and the implications for life on other bodies. Part of this helps us understand Earths past by understanding planetary climate evolution.

Astrobiology investigates prebiotic chemical processes and the elements of life. Astrobiologists seek out potential habitats and constrain the limits of life. They seek to understand how and where life has developed and how it evolves.

Planetary Instruments Definition and Development Program (PIDDP) provide the advanced tools needed for the next generation of exploration. There is a continuing need to develop new instrument and measurement concepts.

Information Technology is a relatively new field that is expected to dominate the next decade. An important part of the job for IT is to organize and archive planetary data and disseminate data to researchers. Another goal is to make smarter spacecraft and infuse high-end computing into spacecraft.

CURRENTLY OPERATING MISSIONS

The Lunar Prospector Extended mission ended July 31, 1999. The mission exceeded all primary science objectives. Lowering the orbit, closer to the Moon, provided 2-10x improved measurements. The major finding from the mission was to provide strong support for "impact" origin of the Moon in which a Mars sized body may have impacted early Earth and the Moon formed from the debris. Another important finding is the possibility of ice in the polar regolith which supports theories of significant cometary contributions to atmospheres of inner planets.

The Galileo spacecraft continues to operate normally; radiation effects continue but are being handled by successive software patches. The Galileo Millennium Mission (GMM) began with the successful Europa encounter on 4 January 2000. A Ganymede encounter (G28) occurred on 20 May 2000. Both of the planned Io encounters (I 24 and 25) were qualified successes. Radiation-induced memory failures required last minute heroics that achieved more than 50% of each encounter's planned data.

Cassini may be the most ambitious science payload ever flown. All Cassini flight system performance continues to be excellent. Successful and accurate flybys of Venus and Earth were accomplished with valuable science data returned during both encounters. Cassini successfully imaged the asteroid Masursky in 1/00, with the first use of Inertial Vector Propagator capability to track a remote sensing target. Development of the science observation strategy and data allocations for Titan and the icy satellites have progressed well. There will be a Jupiter Flyby on December 30 2000. The objectives are to test science acquisition and operations procedures and test ground and flight software prior to arrival at Saturn. We will also accomplish useful Jupiter science. The Science Objectives of Cassini at Jupiter include:
- Atmospheric dynamics, including zoom movie
- Solar wind interaction coordinated with Galileo and Hubble
- Galilean satellite observations, some coordinated with Galileo
- Io dust stream observations coordinated with Galileo
- Jupiter synchrotron emission observations using radar

Arrival and orbit insertion will occur on July 1, 2004. The final Cassini tour selection was made in March, 1999. The mission at Saturn will include:
- Phoebe flyby on June 11, 2004, at a range of 2,000 km on approach to Saturn
- Saturn encounter and Probe entry and relay on November 27, 2004
- 75 orbits of Saturn at inclinations ranging from 0 to 75 deg, full range of solar phase angles
- 44 close encounters with Titan, 28 closer than 1,300 km
- 7 targeted icy satellite flybys at altitudes up to 1,000 km, 27 additional at ranges up to 100,000 km
- Numerous solar and Earth occultations of spacecraft by Saturn, Titan, and rings
- Numerous passes through magnetotail, satellite wakes, and flux tubes
- Science observing time allocations and sequence planning have begun.

NEAR is conducting the first detailed study of a near-Earth asteroid. The importance of this mission is because asteroids are primitive bodies that record conditions of the early solar system. Some near-Earth asteroids may be extinct comets; many are potential Earth impactors. Detailed information on their composition and chemistry will enable understanding of geology, internal structure, and links to meteorites and to life. A detailed understanding of NEA's will help us to assess the threat to Earth and possible mitigation strategies. The NEAR science goals include:
- Eros physical properties, surface composition, surface structure
- Interaction with solar wind
- Search for signs of activity (dust and gas production)
- Coordinated observations by Goldstone (via GAVRT student research program) will enable radar calibrations prior to Saturn arrival.

Stardust, which will return a sample of cometary and cosmic dust to Earth, was Launched February 7, 1999. The first interstellar dust collection occurred Feb 22 - May 1 2000. The collector successfully deployed and re-stowed while commanded motions kept the collector normal to the dust stream. All mechanisms performed as expected and collection of approximately 100 particles is expected. The next major events are the Earth Gravity Assist January, 2001, comet Wild 2 encounter January, 2004, and Sample return, January, 2006.

Deep Space 1 was designed to validate ion propulsion and 11 other advanced, high-risk, important technologies. It successfully completed the primary mission in September 1999 and met or exceeded all mission success criteria. During the primary and extended mission, weoperated the ion propulsion system for > 3500 hours. The engine consumed 21 kg of xenon with the total (v = 1300 m/s. The same (v with conventional propulsion would require > 180 kg propellant. DS1 flew by asteroid 9969 Braille on July 29, 1999, with a closest approach of 28 km. Unfortunately, unexpected response of the camera combined with asteroid brightness lower than the worst-case prediction caused no images to be available for the autotracking system. As a result, we acquired all fields and particles data and very limited imaging and infrared spectrometry data.

Mars Global Surveyor will go into an extended mission operations phase in January. All the instruments and flight systems continue to operate well. The mission has been an enormous scientific success, providing a major change in our view of the red planet. The magnetometer experiment has revealed significant remanant magnetization of the Martian crust. These rmagnetic anomalies in the ancient crust indicate that Mars did have a global magnetic field early on although it has been established that Mars currently has no global magnetic field. We finally have an accurate global topographic map of Mars, the best for any planet, revealing 30-km range of topography, including an incredible level northern hemisphere, that may represent the location of a large ancient ocean. Mineral mapping has revealed two different surface compositions that point to globally distinctive zones of crustal material: volcanic rocks of basaltic composition in the south and andesitic composition in the north. Surprisingly, given the evidence for abundant early water on the surface, no areas of carbonate, sulfate, or quartz have been found. The mineral mapping also provided detection of several coarse-grained hematite deposits, also probably related to water in some way. Abundant and pervasive eolian activity is evidenced by the abundance of dunes, sand sheets, dust cover, and dust devils actually caught in progress. Recently the Mars Observor Camera reported clear evidence for of a sapping origin of many channels from probable melting of ground ice, and possible evidence for recent liquid.

The Mars '98 missions were the major failures that we experienced, having lost both the Mars Climate Orbiter and the Mars Polar Lander. In the final analysis, the MCO failure was caused by a navigation error due to units inconsistency. The MPL failure was most probably caused by spurious signals triggering premature engine cutoff. The DS2 penetrators, which were carried by MPL, failure cause is unknown. Investigation and assessment activities have been concluded. The Solar System Program is already stronger and has received tremendous support from NASA, the Administration, Congress, and the public.

MISSIONS UNDER DEVELOPMENT

Mars 2001 is an important mission for continuing the global characterization of Mars. The mission will provide a vital data base for future landers and rovers. The Mars 2001 Orbiter is instrumented to follow up and test many of the water related science questions that have been raised by the Mars Global Surveyor data. The orbiter is scheduled to launch April 7, 2001. The arrival date is October 21, 2001. The next 76 days will be used to aerobrake into a 2-hour, 400-km range, science orbit. The orbiter will be placed into a near-polar, circular, sun-synchronous orbit. The Orbiter carries three science experiments, the Thermal Emission Imaging Spectrometer (THEMIS), the Gamma Ray Spectrometer (GRS), and the Mars Radiation Environment Experiment (MARIE) which will characterize the Mars radiation environment for radiation-related risk to human explorers. The GRS will acquire a global map of the elemental composition of the surface and determine the abundance of hydrogen in the shallow subsurface. Patterns of the hydrogen distribution can be used to test models of subsurface water and ice distribution. We might expect to see a mid latitude pattern of greater near surface ice if previous models are correct, much like the pattern of channels recently revealed by MGS MOC images. THEMIS will map the mineralogy and morphology of the Martian surface using a high-resolution camera and a thermal infrared imaging spectrometer. The IR images, with about 100m resolution at 10 bands between 6.5 and14.5 microns, (in area about a factor of 100 smaller pixels than TES) could detect small patches of carbonate or other evaporites associated with ephemeral lakes or streams. The 20m imaging mode of THEMIS has the potential to provide a global high resolution map which can better reveal the distribution of water-related features.

Mars Express

The Mars Express Mission is a 2003 mission being developed by the European Space Agency. The Orbiter Science payload is primarily reflight of Mars '96 payload with seven instruments from five nations including the U.S. Instrumens are a Radar Sounder (joint U.S./Italy) a new instrument. The Beagle Lander is furnished by the U.K. consortium. It carries ambitious biological experiment payload. The lander vehicle uses a Russian airbag design. The launches are June 2003 with Mars Orbit Insertion and landing in December, 2003. The Prime Mission is expected to be one Mars Year, through late 2005. The Mars Express NASA Project includes the Radar Sounder MARSIS managed by JPL with antenna, transmitter and RF subsystems furnished by NASA in a joint effort with the Italian Space Agency (ASI). The U.S science includes a Co-PI on MARSIS and 15 U.S Co-Investigators on this and other instruments. We plan telecom interoperability: with NASA Missions.

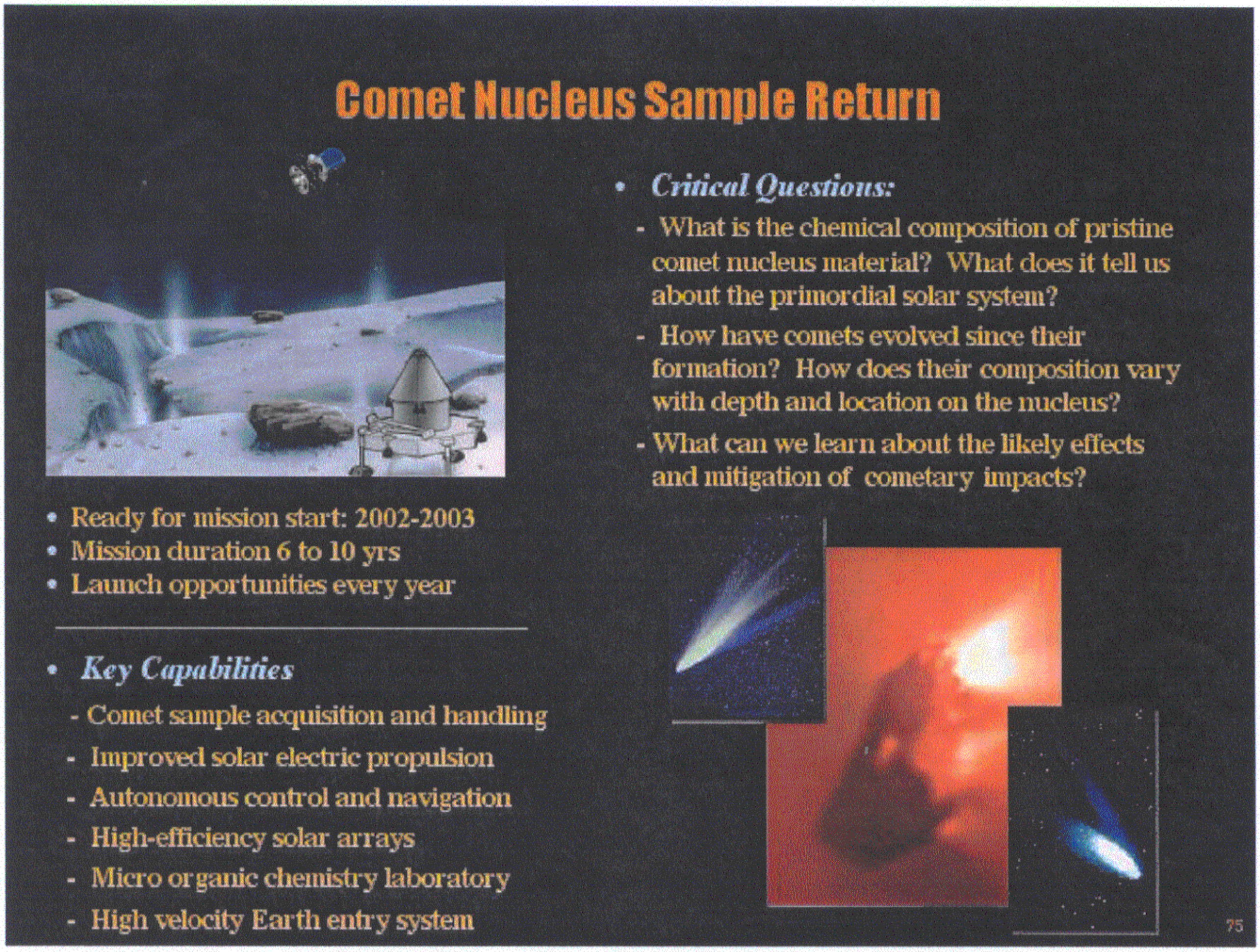
Mars Program replanning

Following the losses of last year, NASA has been leading a major Mars Program replanning effort that began in May and will conclude inNovember 2000. Ideas have been solicited through three separate activities: A Request For Information to the industry, a workshop at the Lunar and Planetary Institute for scientists and technologists, and input of ideas from all the NASA centers. The first major decision has been to send two landers with rovers to Mars in the 2003 opportunity. The landers will use Pathfinder airbag landing systems and carry rovers about ten times larger than the Pathfinder Sojourner rover. The new rovers will carry the Athena suite of instruments originally selected for the cancelled 2001 lander/rover mission. The instruments include a PanCam-MiniTES with high resolution panoramic imaging and mineral mapping capability. Also included is an Alpha X-ray Spectrometer similar to the one on Sojourner. The rover will have a microscope for studying rock surfaces and a device for scraping through any weathering rind that may be present.

FUTURE MISSIONS

In addition to the Discovery and Mars Program lines, the Exploration of the Solar System Theme has the Outer Solar System Exploration Program. The objectives are to develop, launch, and operate the Europa Orbiter, Pluto-Kuiper Express and Solar Probe missions within a funding profile yet to be established. Planned missions will conduct science operations and return, validate and archive science data characterizing Europa, Pluto, and near-Sun and environs. In addition, we will infuse enabling new technology into the flight and ground system developments and conduct the program development and operations in an open manner which contributes measurably to NASA's overall education and public outreach program. The Solar Probe will be managed as an integral part of the Outer Planets / Solar Probe (OP/SP) Project to capitalize on avionics, s/w & operations commonality and to save cost. Two other missions that have a lot of scientific interest, but are further out in time are a Comet Nucleus Sample Return (CNRS) and a Venus Sample Return mission

Comet Nucleus Sample Return will provide crucial insight into the building blocks of the solar system and the processes that shaped the planets, including Earth. CNSR will rest on the foundation of scientific knowledge and technological capability resulting from present and planned missions to comets and asteroids.

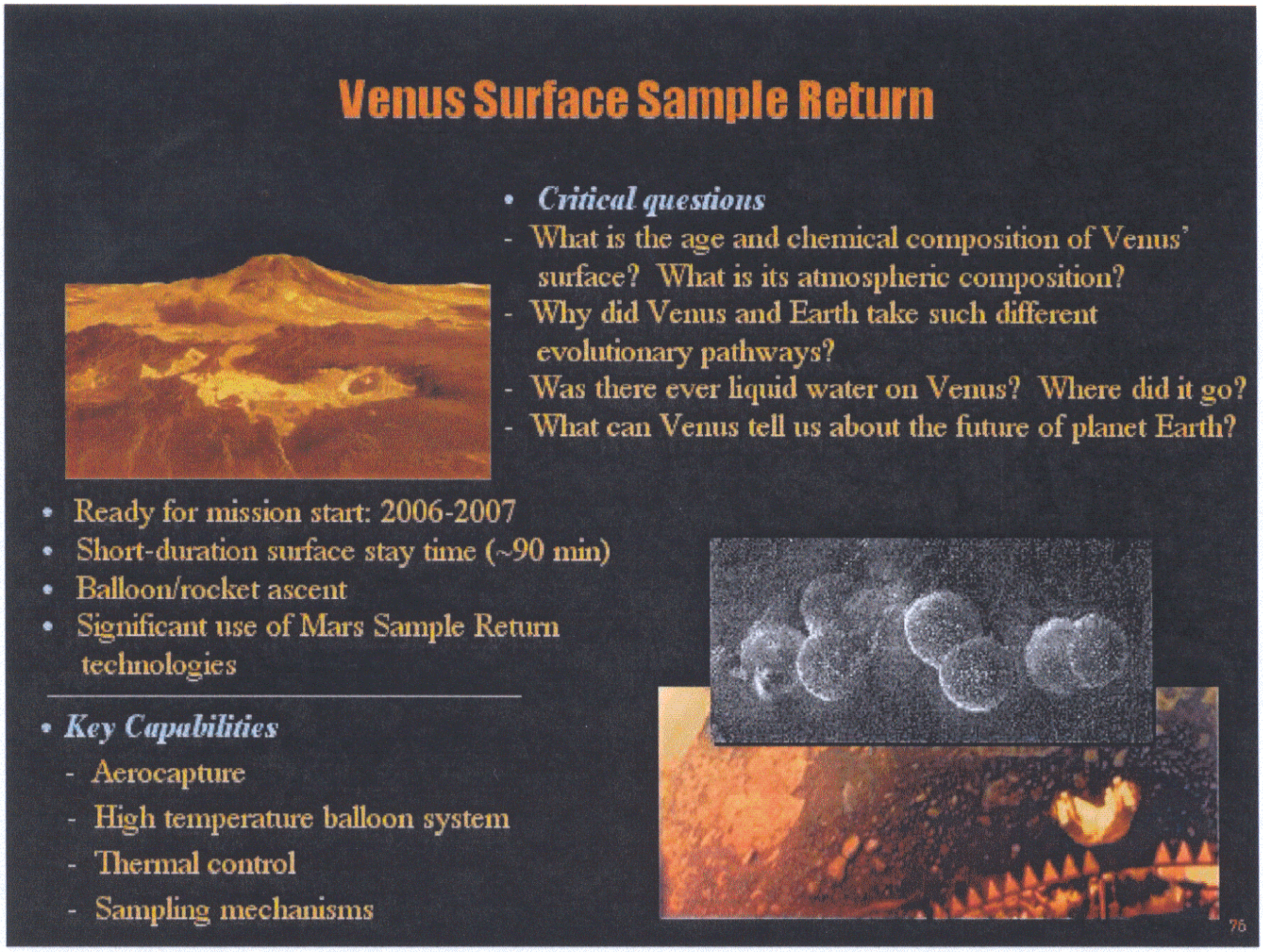


The Venus Surface Sample Return Mission will allow us to answer fundamental questions about the evolution of Earth-like planets. Why did a planet with strikingly Earth-like size, composition, and geologic activity develop such a different surface environment? The answer may lie in a severe "runaway greenhouse" which, like Earth's more mild atmospheric greenhouse, traps solar radiation and warms the planet. But we do not know when or precisely how this global climate change occurred and how it changed Venus into the hot, dry, acidic planet we find today. Understanding this evolutionary divergence has important implications for the study of life-sustaining environments in general as well as for our understanding of Earth's fragile, changing environment. A surface sample return will address the following specific questions:

- What is the age of the Venusian surface?
- What is the composition and origin of Venus' surface rocks?
- What can study of key isotopes tell us about differentiation on Venus?
- How does the oxygen isotopic composition of Venus compare to Earth, Moon, Mars and different
- meteorite parent bodies?
- Did Venus experience a loss of volatile elements and enrichment in iron and refractory elements
- analogous to that which Mercury apparently experienced?

Answers to these questions will enable a tremendously improved understanding of the overall story of Venus and its differences from Earth and the other inner planets.

An additional objective is the return of atmospheric samples, which can be easily collected during the course of the surface sample return mission. This will tell us whether Venus' atmospheric sources and processes differ greatly from Earth's and will do much to illuminate the story of our "twin sister" planet and put our own planetary history in a wider context.



The likely next mission in the program is the Europa orbiter. This mission addresses Key Questions:

- Is there an ocean of liquid water beneath Europa's ice?
- Are there places where the ice is thin or where water reaches the surface?
- Could the Europa environment support pre-biotic chemical processes?